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WATER TUNNEL TESTS
OF THE
2.37 ROCKET PROJECTILE

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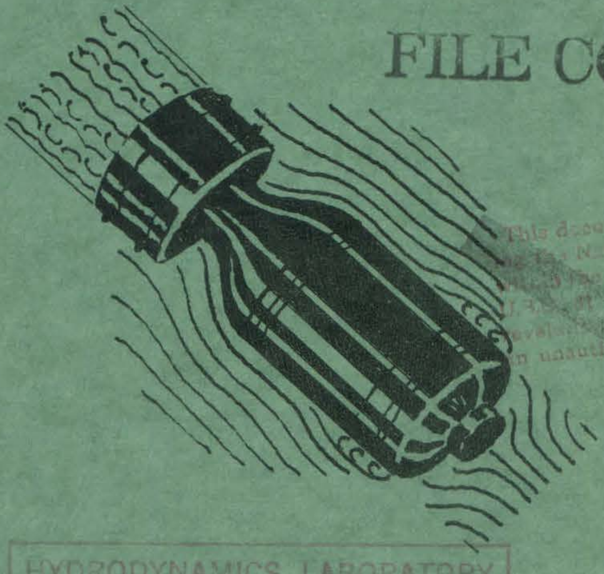

THE HIGH SPEED WATER TUNNEL
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA.

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DIVISION SIX – SECTION 6.1

MEMORANDUM ON WATER TUNNEL TESTS OF A 2.37" ROCKET PROJECTILE WITH HEMISPHERICAL NOSES AND RING TAILS

(Laboratory Designation ND-11)

BY

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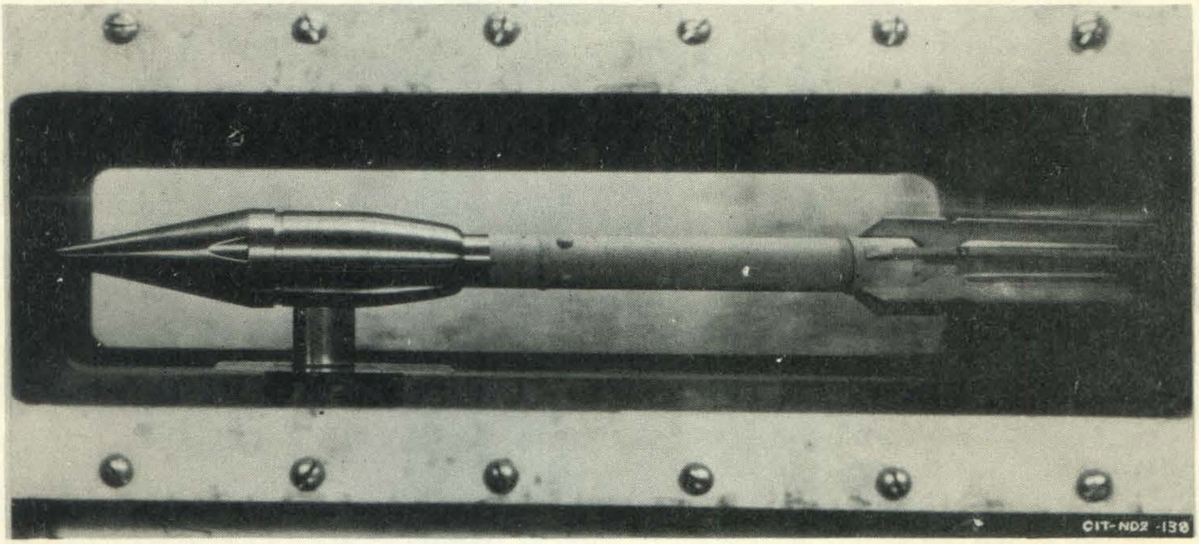


FIGURE 1. 2.37" ROCKET PROJECTILE SHOWN MOUNTED IN WATER TUNNEL WORKING SECTION.

MEMORANDUM ON WATER TUNNEL TESTS OF A 2.37" ROCKET PROJECTILE WITH HEMISPHERICAL NOSES AND RING TAILS

(Laboratory Designation, ND-11)

1. TYPE OF PROJECTILE AND PURPOSE OF TESTS

This report covers water tunnel tests of a full scale 2.37" rocket projectile (designated in the laboratory as projectile number ND-11 Impervium) with two hemispherical noses of different lengths and with three different ring type tails. The purpose of the tests was to compare the performance of the projectile tested with each nose and each tail with the performance of the projectile using its original conical nose cap and fixed-fin tail.[1]

2. TUNNEL INSTALLATION AND DESCRIPTION OF FORCES MEASURED

The tests were conducted in the 14" diameter working section of the High Speed Water Tunnel at the California Institute of Technology.[2] Figure 1 shows the projectile installed in the tunnel. In order to reduce the drag tare to a minimum, the rigid supporting spindle is protected from the flow by the streamline shielding shown in the figure. This shielding which projects to within a few thousandths of an inch of the projectile is held to a small size in order to reduce interference effects.

The forces exerted by the flow on the model can be resolved, in general, into a drag force parallel to the flow, a cross wind force normal to the flow, and moment or torque acting about the point of support. These are the forces measured during the tests. The moment exists only if the model is not supported at the point of application of the resultant of all the hydrodynamic forces. It is clear that the magnitude and sense of the measured moment will change if the point of support is shifted along the body.

The water tunnel tests give results which are applicable in either air or water for velocities below that of sound. For velocities in the neighborhood or above that of sound the results will not apply. The data presented in this report have not been corrected for scale effect, tare or interference of the model support. However, they are believed to be reliable since they agree closely with data obtained from full scale projectiles in free flight.

3. REPRESENTATION OF TEST DATA

The hydrodynamic characteristics are presented in the form of curves of force coefficients as functions of the angle of yaw. In addition, the distance of the center-of-pressure from the nose of the

(1) Figures refer to references listed at the end of this report.

projectile expressed as a fraction of the length of the projectile is plotted against yaw angle. The center-of-pressure is defined as the points at which the resultant hydrodynamic force vector intersects the axis of symmetry of the model.

The force coefficients, C_D, for drag and C_C, for cross wind force are expressed as:

$$C_D = \frac{D}{\rho \frac{V^2}{2} A_D}$$

and

$$C_C = \frac{C}{\rho \frac{V^2}{2} A_D}$$

where

D = measured drag force in lbs

C = measured cross wind force in lbs

ρ = density of water in slugs per cu ft

A_D = area in sq ft of a cross section at the cylindrical portion of the projectile head taken normal to the geometric axis of the projectile (= 2.98 sq in, i.e. dia = 2.25 in, for this projectile)

V = mean relative velocity between the water and the projectile in ft per sec

The moment coefficient is expressed as:

$$C_M = \frac{M}{\rho \frac{V^2}{2} A_D L}$$

where

M = moment in in-lbs measured about any particular point on the geometric axis of the projectile

L = overall length of the projectile in in. (For all combinations of the projectile discussed in this report L is taken as 21 3/8")

The distance from the nose to the center-of-pressure (center-of-pressure distance) as a fraction of the overall projectile length is expressed as:

$$\frac{\bar{X}}{L} = \frac{L' + L''}{L} = \frac{L'}{L} + \frac{1}{L}\left(\frac{M}{C\cos\Psi + D\sin\Psi}\right)$$

where

L' = distance in in from the projectile nose to the center of moments

L'' = Distance in in from the center-of-pressure to the center of moments

Ψ = yaw angle in degrees

When M is the measured moment the center of moments is at the support point of the model and L'' then is the distance from the support point to the center-of-pressure. The signs of the moment, M, the cross wind force, C, and the yaw angle, Ψ, are such that M and Ψ have the same sign when they oppose each other and C and Ψ have the same sign when they act in the same direction. Thus, for example, a positive or clockwise moment will tend to reduce a positive or counter clockwise yaw angle, while the corresponding positive cross wind force will act to the left (when facing in the direction of the trajectory).

4. DESCRIPTION OF THE PROJECTILE PARTS

The rocket projectile is made up of a head or body in which the principle explosive charge is placed, a boom or "motor" which carries the propulsive charge, and a tail attached to the end of the boom. The original rocket was composed of a head with a conical nose and a tail with six fixed-fins. This projectile is shown in Figure 2.

Two hemispherical noses were constructed to replace the conical nose of the original projectile. One is long so that the overall length of the projectile is unchanged. The other is shortened so that the projectile length is reduced by 3 3/4 inches. Both new noses have the same diameter of 2 1/4 inches. This is slightly less than the maximum diameter of the conical nose but is equal to the diameter of the cylindrical portion of the projectile head so that the profile of the head and hemispherical nose is without disturbing projections. Photographs of the entire projectile with the long and short noses are shown in Figures 3 and 4.

Three tails (designated by the numbers 17, 18, and 21) were constructed to replace the original fixed-fin tail. These are ring type tails made of a cylindrical shroud ring held concentric with the geometric axis of the projectile by radial fins. The construction details are shown by the drawings of Figures 18, 19, and 20. The tails were made interchangeable by building the tail structure on to the removable motor nozzle units. The nozzles were internally threaded on the upstream end for screwing to the boom. In each case the nozzle unit was built up or "faired", as shown by the shaded areas in the above figures to eliminate the abrupt change in cross-section. The shroud is supported by three radial fins spaced at 120° for each tail. The length of the shrouds and their locations relative to the motor nozzle unit are different. The shroud length of Tail No. 17 equals one diameter (2.31" actually), and it is mounted so that its upstream or leading edge is well forward on the motor nozzle. Tail No. 18 has a short shroud length of only 0.6 diameter and is mounted with its upstream edge farther back. Tail No. 21 has the longest shroud length of 1.08 diameters and is mounted with its leading edge still farther back. The effect of the location of the leading edge is to change the "entrance" area between the shroud ring and the tapered portion of the nozzle. This entrance area is the annular area between the shroud and the nozzle measured normal to the relative flow direction. Photographs of the complete projectile with each of the three tails are shown in Figures 5, 6, and 7. Photographs showing each unit in detail are found in Figures 8 to 16 inclusive.

The overall projectile length is reduced when any one of the three ring tails are used with the original head and boom. Figure 17 shows the short ring tail (No. 18) mounted with a long boom so that the overall projectile length is 21 1/2".

5. TEST RESULTS

Figure 21 compares the results of the measurements for each of the combinations tested with those for the original projectile having a conical nose and fixed-fin tail. Values of the center-of-pressure distance and the force and moment coefficients are plotted as functions of the yaw angle. The values shown are approximate values obtained by fairing and averaging the actual test data to eliminate the irregularities caused by asymmetry built into the projectile.[3] It is believed that these curves closely approximate the performance to be obtained from a perfectly symmetrical rocket. This treatment was used because the performance for the non-symmetrical rocket is different for every plane of yaw so that a very complicated motion in flight must be expected. Such behavior will certainly introduce extra dispersion or scatter when the rocket is fired. While the complicated behavior predicted from tests of an asymmetrical rocket is probably typical of many projectiles it cannot be said with assurity that it is representative of a large group of projectiles without examination of the limits of asymmetry to be encountered. Furthermore, the non-symmetrical effects tend to mask the influence of changes in design so that proper interpretation of the actual test data is difficult. For these reasons it seems more valuable to study the symmetrical case.

The center-of-pressure distance is given as a fraction of the overall length of the original projectile (21 3/8"). For most runs this distance is measured from the nose tip. For the short hemispherical nose only, this distance is measured from a point 3 3/4" ahead of the nose tip, so that the $\bar{x}/L$ values relative to the projectile head and boom are comparable to those for the other combinations. This relationship is shown more clearly by the scale drawings of Figure 22, where the short hemispherical nose is so placed that the origin for the $\bar{x}/L$ measurements is the same as for the other projectiles.

In Figure 21 the curves labeled 5a and 6a are for the projectile with the long and the short hemispherical noses respectively. The center-of-pressure distance for the short nose is 0.56L and for the long nose is 0.43L. These figures are in comparison with the value of 0.48L for the original projectile. This shift in $\bar{x}/L$ can be explained qualitatively as follows. Tests of cylindrical bullet shaped bodies (4) which are approximately the same as the heads of these projectiles, show the center-of-pressure to fall between 0.27L for long bullets and 0.34L for very short ones. Thus as the head is shortened by cutting off the nose, the point of application of the cross wind force acting on the head must move back toward the projectile tail both because of the change in length and because of the inherent shift in $\bar{x}/L$ with length. This, of course, contributes to the rearward movement of the center-of-pressure.

The significance of the $\bar{x}/L$ shift is shown more clearly by the graphical representation of Figure 22 where the locations of the center-of-pressure and center-of-gravity are shown to scale. The values of the center-of-gravity distances in this figure are approximate and are calculated for the case when the propellant in the projectile motor is fully spent. It is clear that the short nose projectile offers the largest margin for stability as measured by the distance between the C.G. and C.P. In fact for the long hemispherical nose the center-of pressure falls at the center-of-gravity so that this form of the projectile can be expected to be unstable. These conclusions can also be obtained from an examination of the moment coefficients calculated about the center-of- gravity. For the short nose no curve is shown since there is zero moment about the C.G. Unfortunately the short nose modifies the projectile head more than is desirable. Hemispherical noses with intermediate lengths will probably show intermediate values of $\bar{x}/L$ and of the center-of-gravity distance, with the stability margin decreasing from the value shown for the short nose toward zero. The measured drag decreases as the projectile head is reduced in size. This is consistent with the reduced surface in contact with the flow.

The ring type tails were designed with the multiple objective of improving the margin for stability, reducing the drag of the projectile, simplifying the construction, and providing a rugged tail which would remain symmetrical with reasonably rough handling. The curves of Figure 21 labeled 11b, 12, and 17 show the results of tests using the conical nose and regular boom with the ring tails numbers 17, 18, and 21 respectively. The values of the center-of-pressure distance, $\bar{x}/L$, show Tail No. 21 to have the greatest of 0.54L. This is in comparison with 0.53L for Tail No. 17 and 0.52L for Tail No. 18. These values indicate an improvement over the figure of 0.48L for the original projectile. Referring to Figure 22 it is seen that the locations of the centers-of-gravity are slightly different with each tail. The result is that both tails Nos. 18 and 21 show the same margin for stability in terms of the distance between the C.G. and C.P. Comparing with the original projectile with fixed-fin tail this is seen to be an appreciable improvement. Here it should be emphasized that the C.G. locations were calculated using the actual weights of the brass test tails. In view of the objective of ruggedness these tails are probably heavier than necessary and they can be lightened by decreasing the thickness of the fins and shroud. They also might be lightened by using other materials. Such modifications should contribute to a still larger margin for stability.

It is interesting to note that in each case the tail with the longer shroud ring has the larger $\bar{x}/L$ value. It is not certain whether this is caused by the shroud length itself or is the result of a different location of the shroud relative to the nozzle. As described in Section 4 the shroud location affects the area between the shroud ring and the motor nozzle. This results in different amounts of water (or air) passing through the ring. Since Tail No. 18 is actually No. 17 with both leading and trailing edges of the shroud cut back, it is felt that the length itself has some significance. This is consistent with information from tests of other projectiles which showed the center-of-pressure distance to be increased as the shroud length was increased.

Each of these ring tails shortens the overall length of the projectile. A test was made with Tail No. 18 using a longer boom so that the projectile length was approximately equal to its original value. This movement of the tail surfaces rearward caused the center-of-pressure to move back to 0.54L (as against 0.52L with the short motor boom). Unfortunately the simultaneous shift of the center-of-gravity more than offset the gain in $\bar{x}/L$ so that the resulting performance indicated less stability margin. The center-of-gravity distance was calculated assuming an extension of the same type and weight of motor boom.

Table I presents a tabulation of the drag coefficients taken from Figure 21 for zero yaw angle.

TABLE I

DESCRIPTION OF PROJECTILE

RUN NO.	HEAD	BOOM	TAIL	C_D AT $\psi = 0$
3a	Conical	Regular	Fixed-Fin	0.30
5a	Long Hemisphere	Regular	Fixed-Fin	0.31
6a	Short "	Regular	Fixed-Fin	0.27
11 b	Conical	Regular	No. 17	0.29
12	Conical	Regular	No. 18	0.24
15	Conical	Long	No. 18	0.23
17	Conical	Regular	No. 21	0.18

It is seen that the ring tails show a progressive reduction in drag with Tail No. 21 giving a value of 0.18. This value is comparable to that of other good projectiles. The improvement is explained by two principle features. The first is the effect of the "entrance" area, the annular space between the shroud ring and the forward edge of the motor nozzle. As was explained in Section 4 this area was increased for Tails Nos. 18 and 21 by moving the leading edge of the shroud back. This enlarged area offers less resistance to the flow of the water (or air) through the ring. It is felt that this is responsible for the largest portion of the drag reduction. In addition, the edges of the shroud and fins of Tails Nos. 18 and 21 were rounded and faired more carefully. For Tail No. 21 the motor nozzle itself was faired or "streamlined" so that a minimum disturbing projection occurred at the upstream edge where the nozzle was screwed to the motor boom. The curved profile given to the nozzle is shown clearly on the detail drawing of Figure 20. A comparison of the projection occuring without and with fairing is shown by the photographs of Figures 5 and 7 for Tails Nos. 17 and 21. After the initial tests of Tail No. 18 the nozzle projection was faired similarly to that of No. 21 (see the change note on Figure 19) and retested. The measured drag was reduced a small amount by this change.

6. SUMMARY

It is clear that the margin for stability can be increased by using a ring tail or by using a short hemispherical nose. However, the use of the hemispherical nose is subject to some functional limitations, and in addition necessitates a new head design. The ring tail effects an appreciable increase in stability and also offers the advantages of simplicity and ruggedness. The margin for stability can be increased further by reducing the weight of the ring tail without sacrificing its advantages.

It should be emphasized that in changing the design of any part of the projectile to improve the stability, consideration should be given to the effect on the location of the center-of-gravity as well as to the effect on the location of the center-of-pressure. For example, in the case of the use of the long boom with Tail No. 18 the center-of-pressure was successfully moved back. However, the net result was a decrease in the stability because the center-of-gravity moved back even farther.

The present experiments have shown that by substituting a ring tail for the original fixed-fin tail the distance between the C.P. and C.G. can be increased appreciably and hence that the stability can also be increased. However, it should be noted that experience has shown that to obtain adequate stability for a normal fin stabilized projectile, the distance between the C.P. and C.G. should be from 12% to 18% of the overall length. On this basis none of the projectiles tested was sufficiently stable and further development is necessary.

Tail No. 21 showed the least drag. This is attributed mainly to the increased annular opening between the nozzle and the shroud although the fairing and streamlining of the fins, shroud and nozzle are also of appreciable importance.

It should be remembered that the test results and discussion presented in this report apply to symmetrical projectiles. As was emphasized, asymmetry in the construction of the rocket can be expected to cause a very complicated motion in flight and certainly must introduce extra dispersion or scatter when the rocket is fired. For this reason it is recommended that considerable thought be given to methods of obtaining symmetry.

References:

(1)$_a$ "Memorandum on Water Tunnel Tests of a 21 3/8" Rocket Projectile " by R. T. Knapp, HML Rep. No. ND-11, November 19, 1942.

(1)$_b$ "Memorandum on Water Tunnel Tests of a 2.37" Rocket Projectile with Collapsible Type Tails " by R. T. Knapp, HML Rep. No. ND-11.1, January 20, 1943.

(2) "The High Speed Water Tunnel at the California Institute of Technology " by R. T. Knapp, V. A. Vanoni and J. W. Daily, June 29, 1942.

(3) For a more complete discussion of the effects of asymmetry and method of approximating the performance curves for symmetrical projectiles, see reference (1)

(4) See the Report "Memorandum on water Tunnel Tests of 2" Diameter Projectiles with Hemispherical Noses and Square Ends " by R. T. Knapp, HML Rep. No. ND-10 November, 1942.

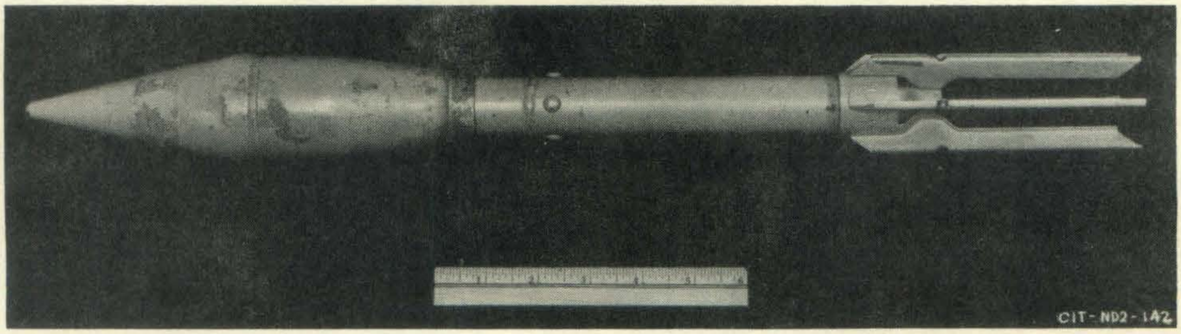


FIGURE 2. 2.37" ROCKET PROJECTILE WITH ORIGINAL CONICAL NOSE AND FIXED–FIN TAIL.

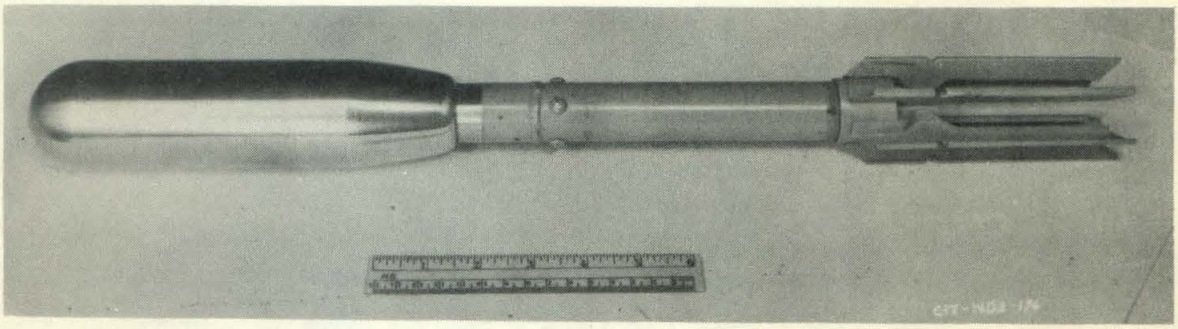


FIGURE 3. ROCKET PROJECTILE WITH LONG HEMISPHERICAL NOSE AND FIXED–FIN TAIL. NOTE THE SMOOTH PROFILE OF NOSE AND HEAD.

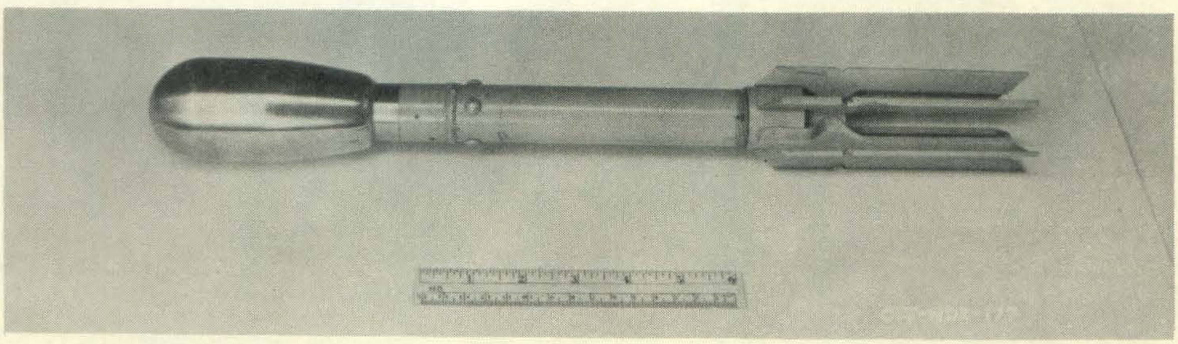


FIGURE 4. ROCKET PROJECTILE WITH SHORT HEMISPHERICAL NOSE AND FIXED–FIN TAIL. NOTE THE SHORT HEAD.

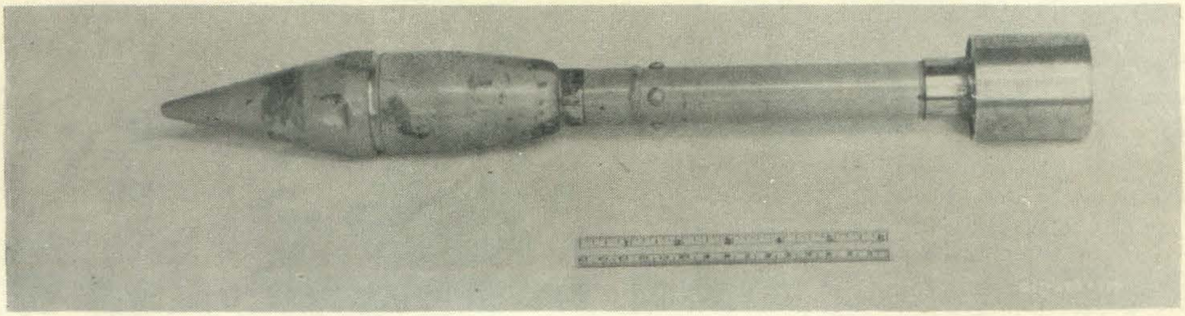


FIGURE 5. 2.37" ROCKET PROJECTILE WITH NO. 17 RING TAIL. NOTE THAT SHROUD HAS A LENGTH OF ONE DIAMETER AND IS MOUNTED WITH LEADING EDGE WELL FORWARD ON MOTOR NOZZLE.

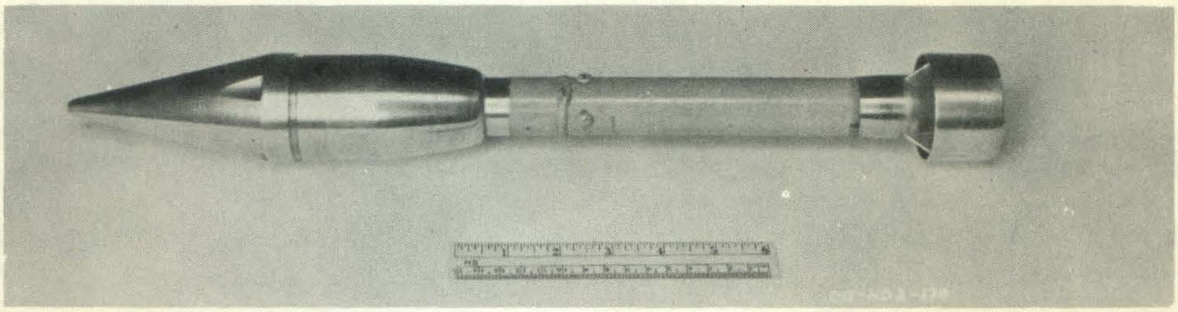


FIGURE 6. ROCKET PROJECTILE WITH NO. 18 RING TAIL. THE SHROUD HAS A LENGTH OF 0.6 DIAMETERS AND IS MOUNTED WITH LEADING EDGE FARTHER AFT THAN FOR NO. 17.

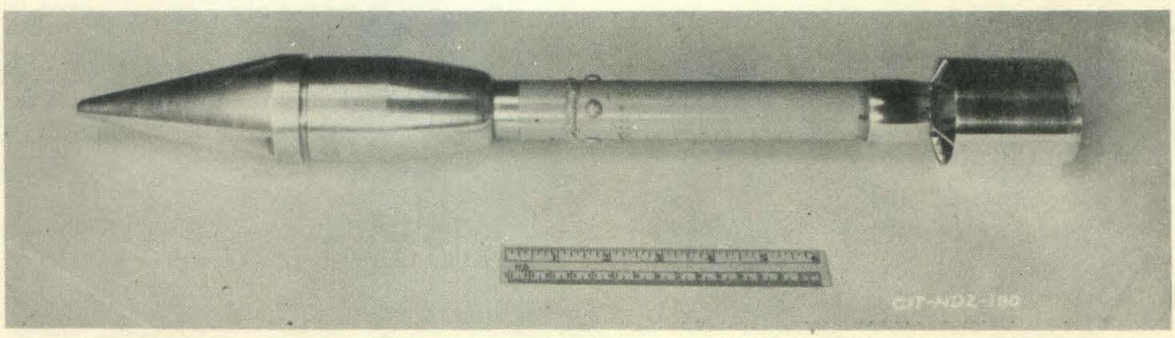


FIGURE 7. ROCKET PROJECTILE WITH NO. 21 RING TAIL. THE SHROUD HAS A LENGTH OF 1.08 DIAMETERS AND IS MOUNTED WITH LEADING EDGE FARTHER AFT THAN FOR NOS. 17 OR 18.

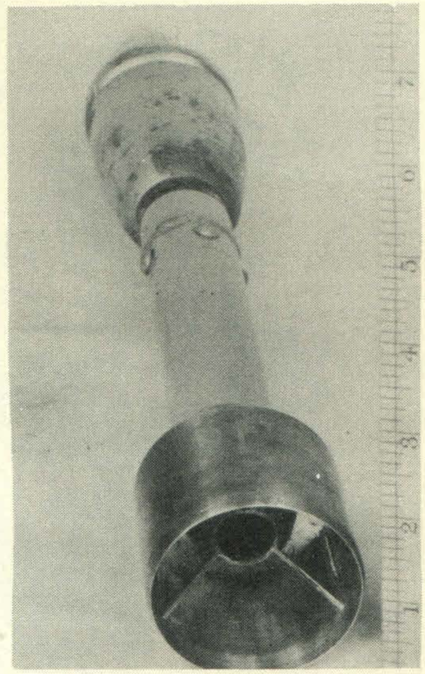


FIGURE 8. ROCKET PROJECTILE WITH RING TAIL NO. 17 VIEWED FROM MOTOR END.

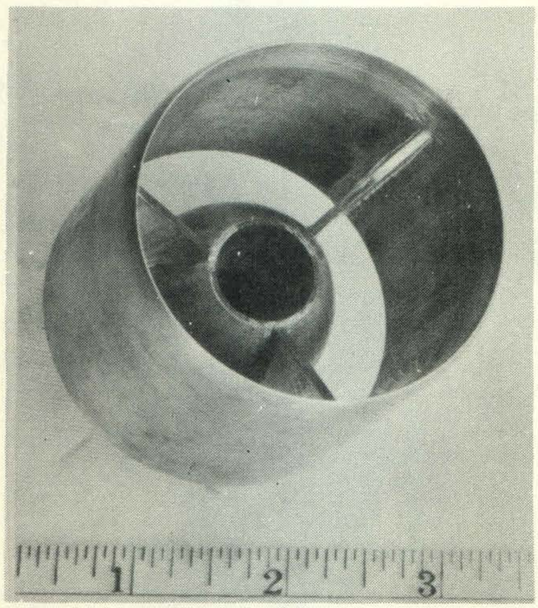


FIGURE 9. CONSTRUCTION DETAILS OF RING TAIL NO. 17.

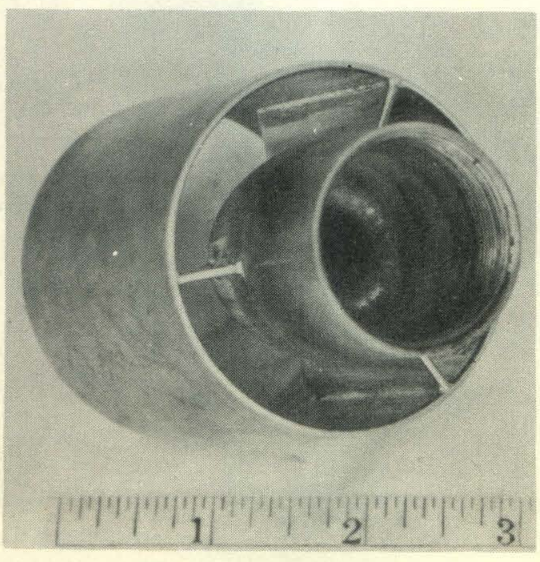


FIGURE 10. CONSTRUCTION DETAILS OF RING TAIL NO. 17.

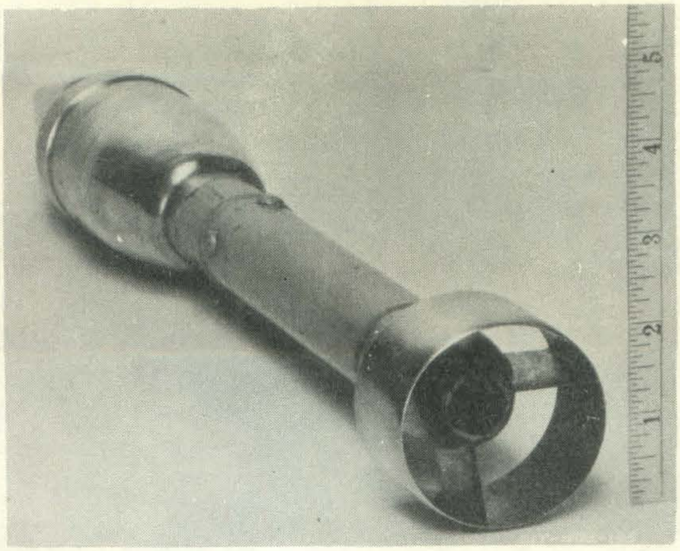


FIGURE 11. ROCKET PROJECTILE WITH RING TAIL NO. 18 VIEWED FROM MOTOR END.

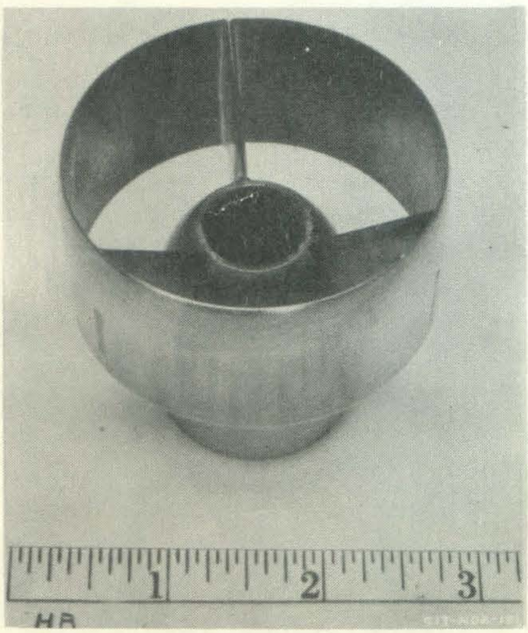


FIGURE 12.

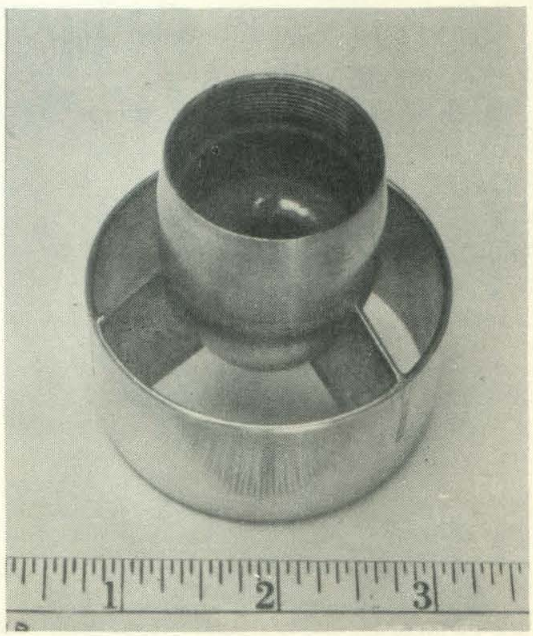


FIGURE 13.

CONSTRUCTION DETAILS OF RING TAIL NO. 18.

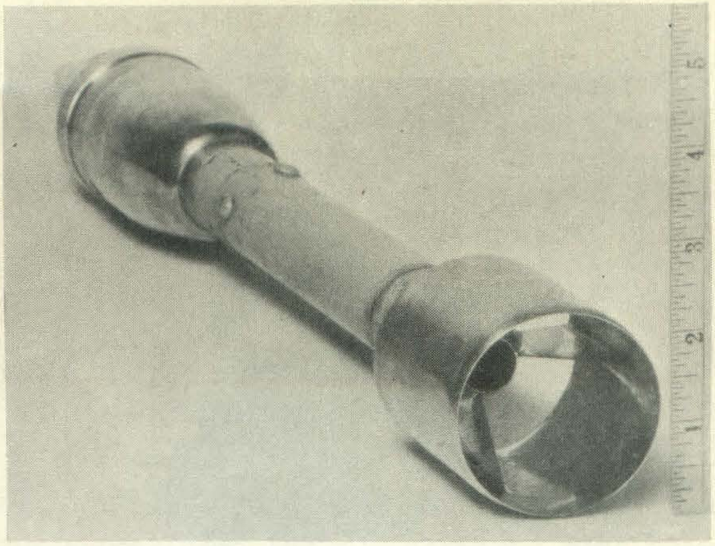


FIGURE 14. ROCKET PROJECTILE WITH RING TAIL No. 21 VIEWED FROM MOTOR END.

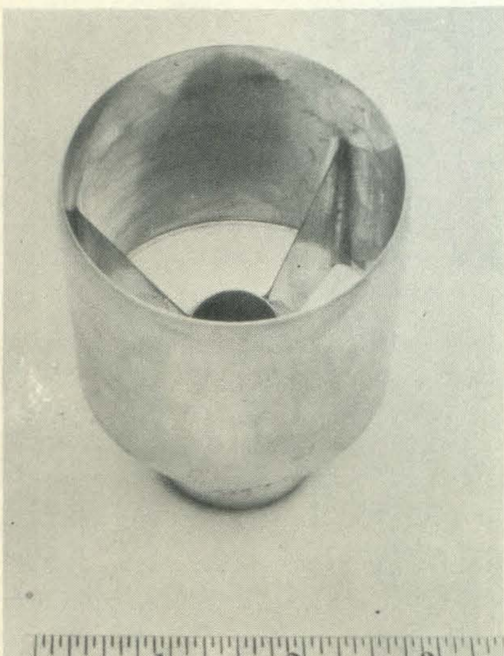


FIGURE 15.

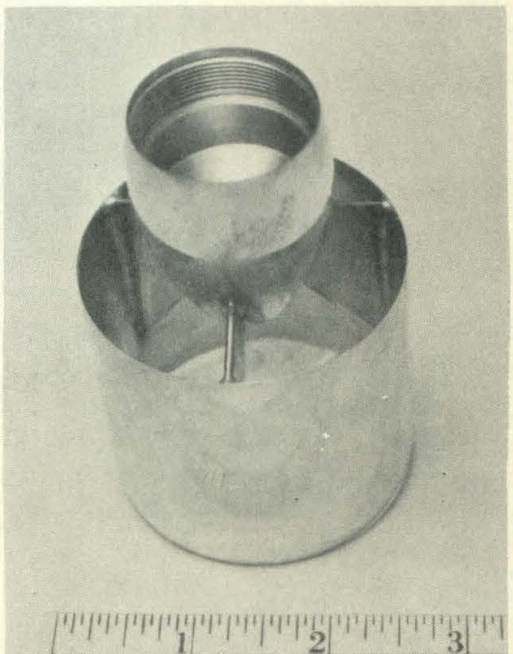


FIGURE 16.

CONSTRUCTION DETAILS OF RING TAIL No. 21.

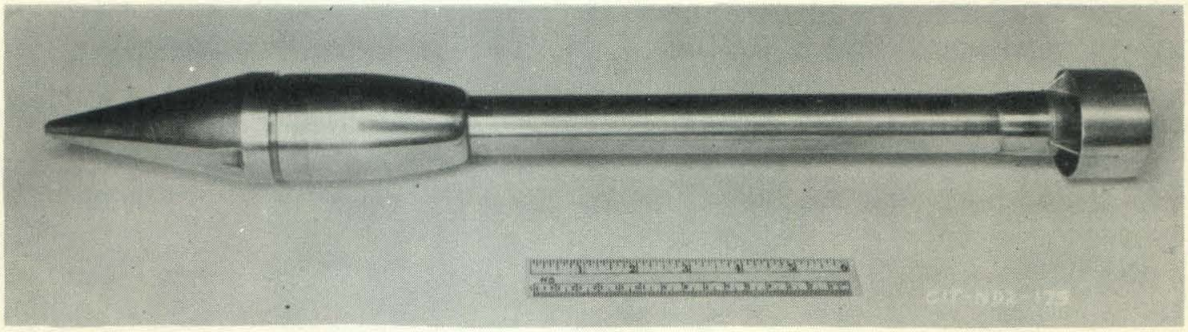
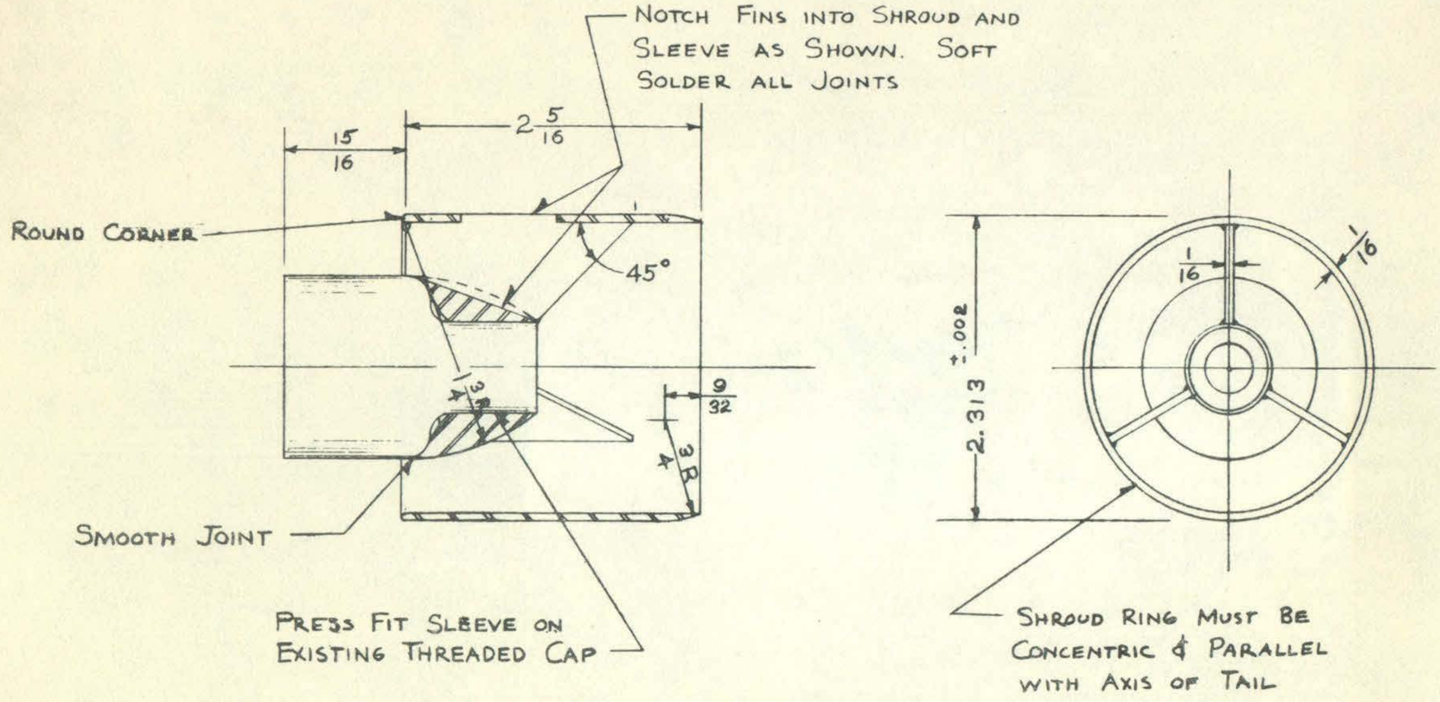


FIGURE 17. 2.37" ROCKET PROJECTILE WITH NO. 18 RING TAIL USING LONG MOTOR BOOM. THE OVERALL LENGTH OF THIS ASSEMBLY IS 21 1/2".



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MAT'L - YELLOW BRASS

HYDRAULIC MACHINERY LABORATORY CALIFORNIA INSTITUTE OF TECHNOLOGY	
MODEL TAIL #17	
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FIG. 18

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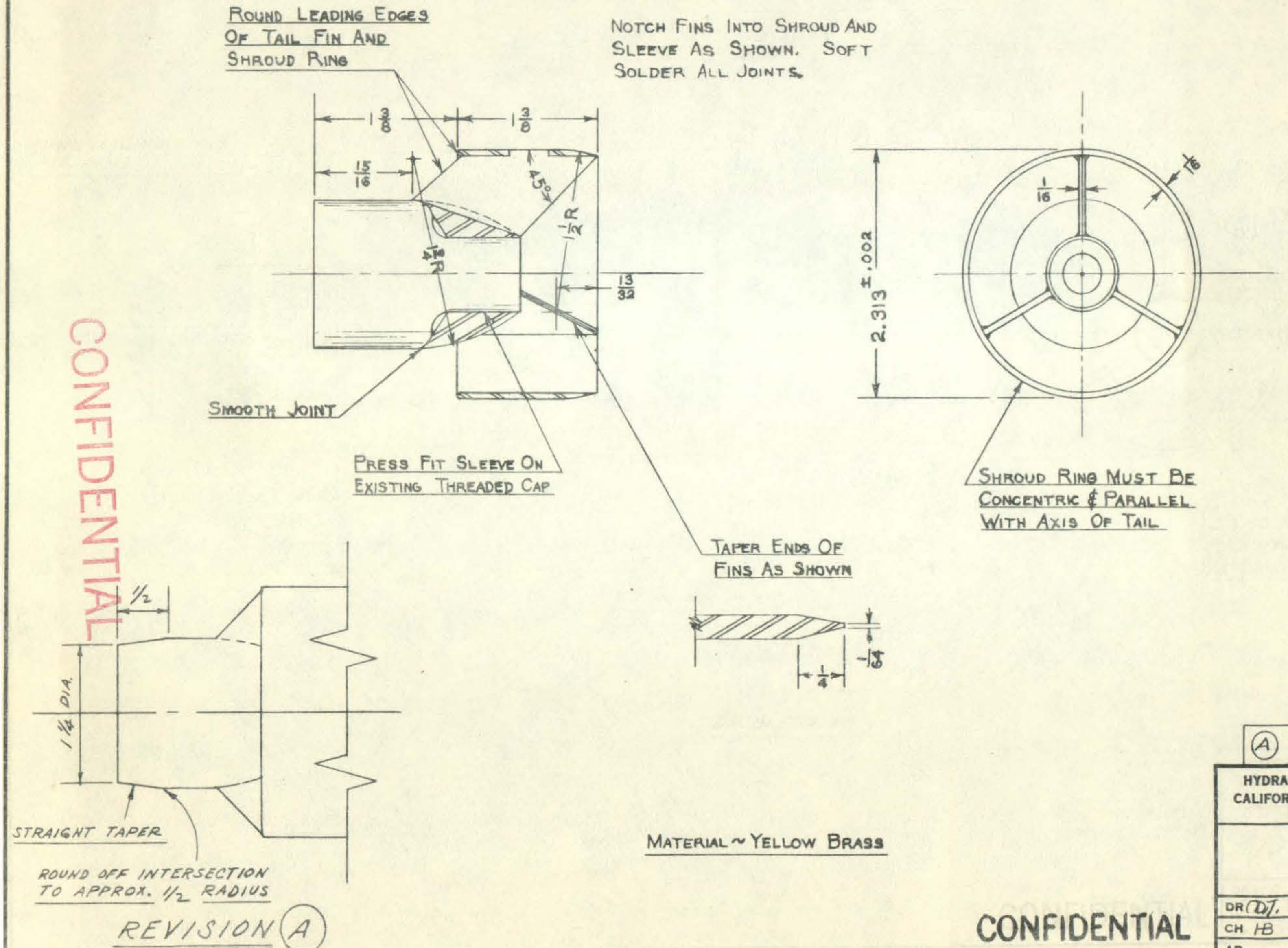

(A) HUB END TAPERED 2-1-43 C.R.A.

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CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

MODEL TAIL
Nº 18

DR D.J. 1-23-43	SCALE FULL
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FIG. 19

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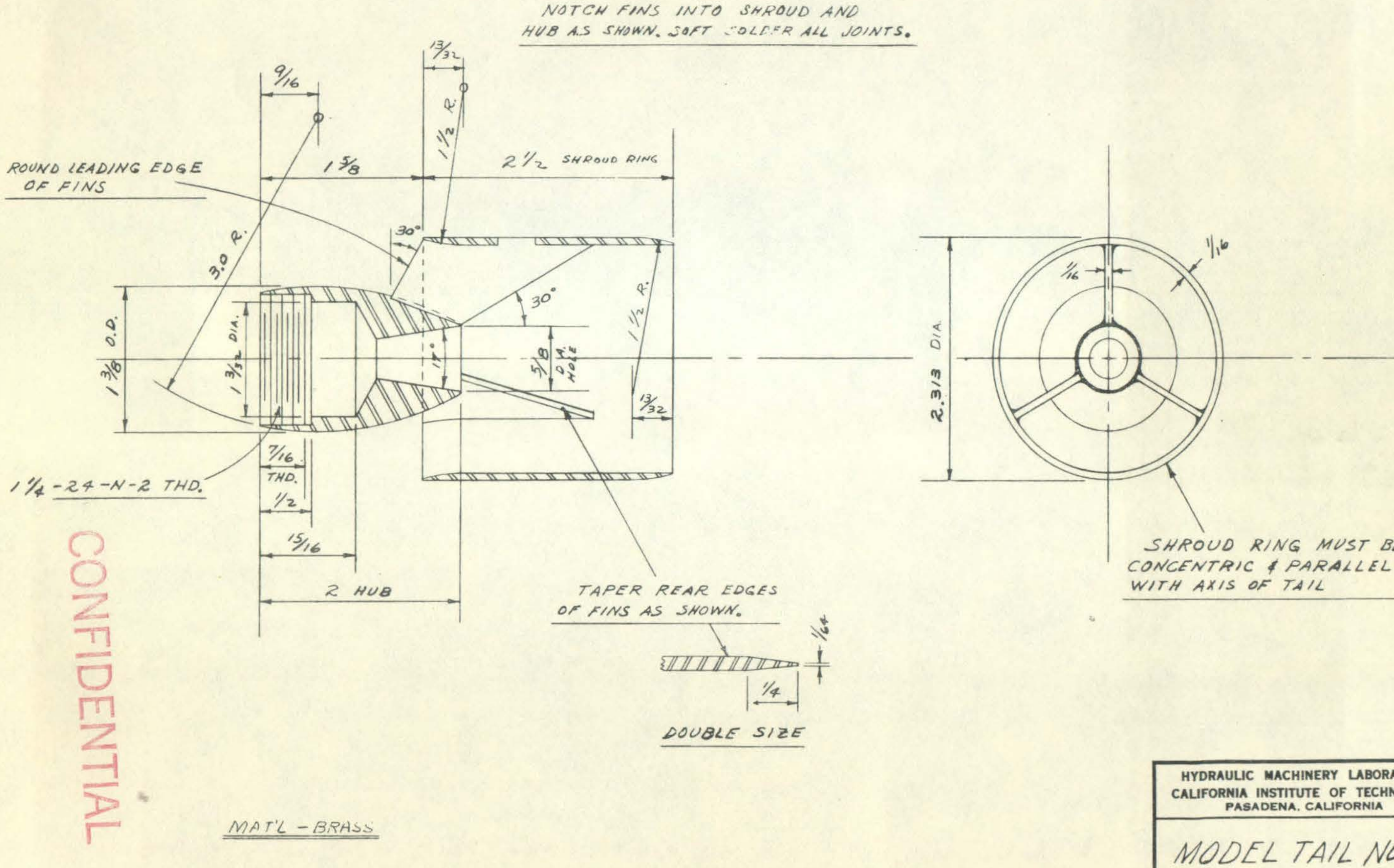

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MODEL TAIL NO. 21

DR CRA 2-3-43	SCALE ~ 1/1 & 2/1
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FIG. 20

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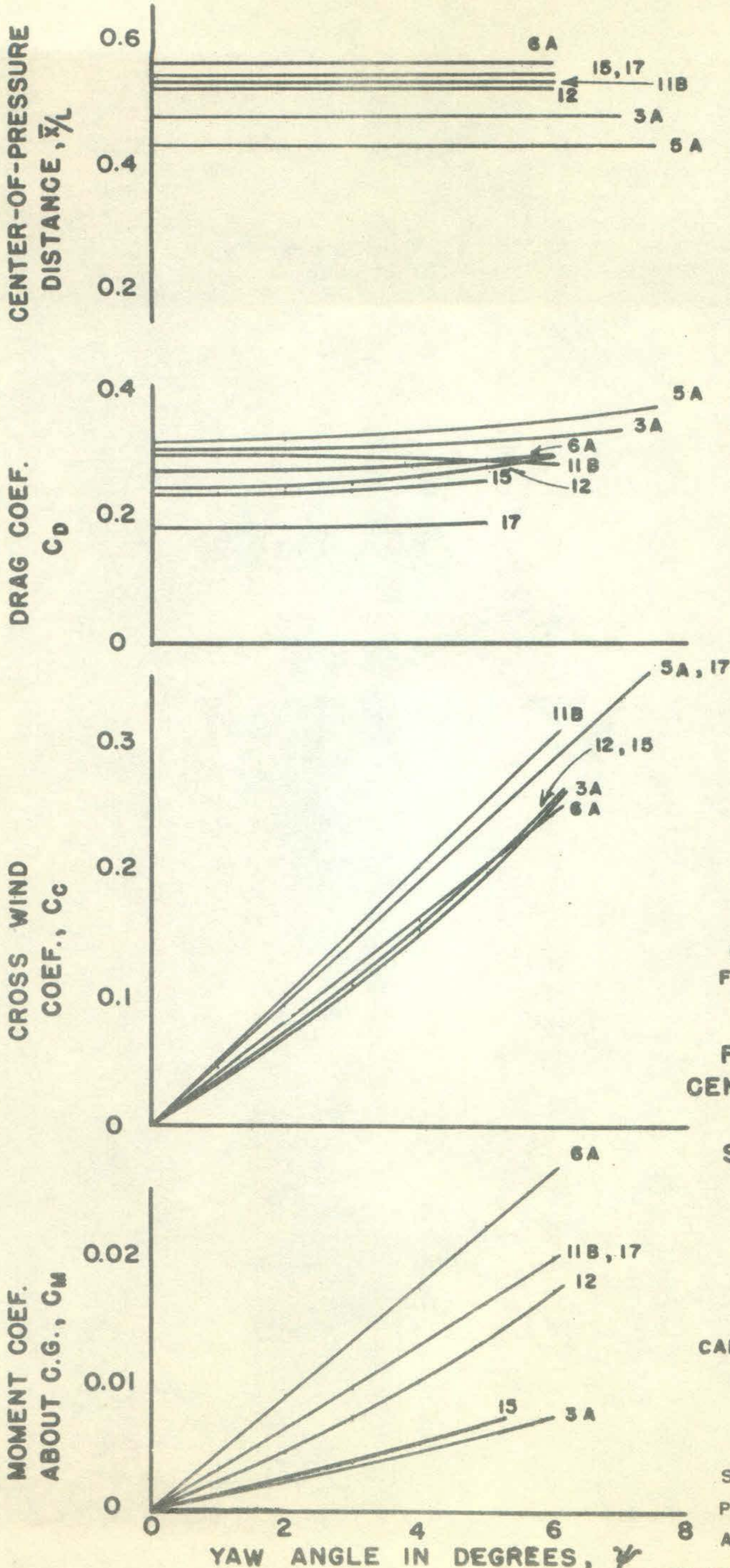

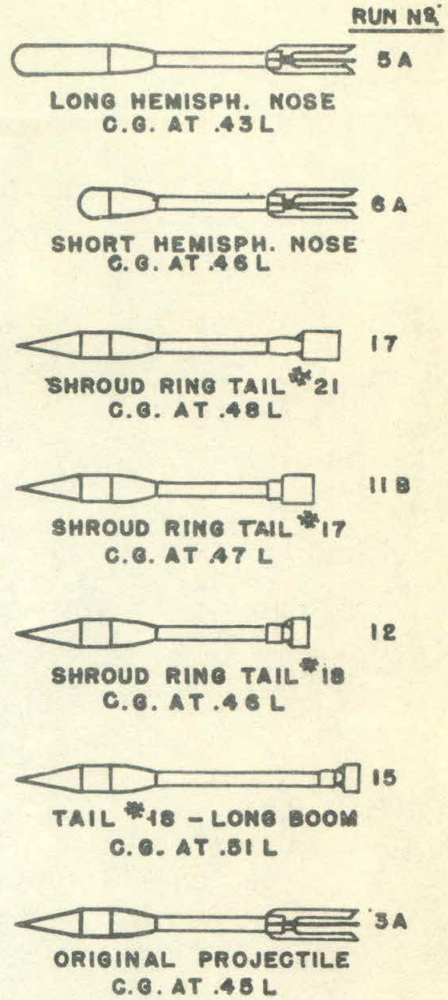

2.37" ROCKET PROJECTILE
CONICAL AND HEMISPHERICAL NOSES—
FIXED FIN AND SHROUD RING TAILS

FORCE COEFFICIENTS AND CENTER-OF-PRESSURE DISTANCE CALCULATED FOR SYMMETRICAL PROJECTILE

THE HIGH SPEED WATER TUNNEL
AT THE
CALIFORNIA INSTITUTE OF TECHNOLOGY

SHEET NO. ND11-613-L   RUNS 3A, 5A, 6A, 11B, 12, 15, 17
PRINT NO. ______
ASSIGNED TO ______ TESTS JAN-FEB 1943

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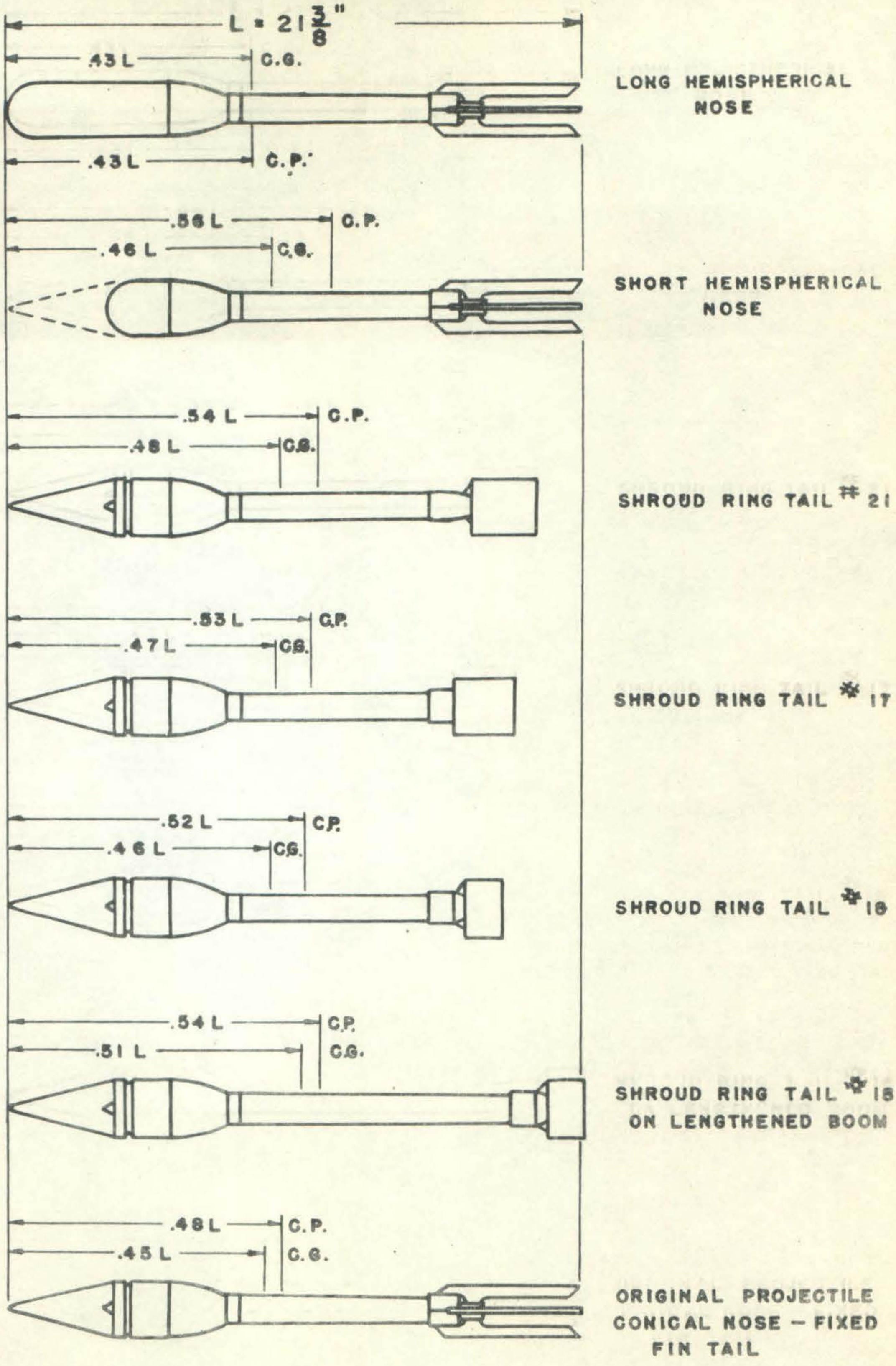

HYDRAULIC MACHINERY LABORATORY CALIFORNIA INSTITUTE OF TECHNOLOGY

DR	2.37" ROCKET PROJECTILES	SCALE
CH	SHOWING C.G. & C.P. LOCATIONS	
AP	DRAWN TO SCALE	HD 11-614-L

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FIG. 22

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